A New Approach Combining Surrounded-Element and Compression Methods for Analyzing Reconfigurable Reflectarray Antennas

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***Abstract*—An efficient technique to provide fast and accurate analysis of large-scale and complex reconfigurable reflectarray antennas is presented and validated. The method combines the surrounded cell approach and the compression technique to analyze the global array. It takes into account the mutual coupling effects and the numerical complexity is reduced. Only a minor electromagnetic simulation and a fast post-processing are required.**

***Index Terms*—Reconfigurable reflectarray, rigorous analysis, surrounded cell approach, compression technique.**

I. Introduction

Reflectarrays [1]-[4] have received increasing attention in the last years, especially in space and defense applications. Reflectarray is an advanced antenna technology that combines key features of reflectors and phased array antennas.

This type of antenna is an array of radiating elements, which is illuminated by a primary feed source. The radiating elements reflect the incident wave with prescribed phase shifts to form a desired radiation pattern.

A reflectarray can be designed as a low profile antenna with high gain. The complex feed network that characterizes phased array antennas is not required anymore.

For passive reflectarrays, the phase of the reflected field can be controlled by varying elements geometry such as a slot or a patch length [5].

Reconfigurable reflectarrays are attractive for implementing reconfigurable patterns. The cells have the same geometry and the dynamic phase control is achieved by electronically varying active loads inserted in each radiating cell. Analog or binary control can be carried out using MEMS [6]-[7], PIN diodes [8] or varactors [9].

Reflectarray electromagnetic analysis is a computationally challenging task given that these antennas are electrically large. Furthermore, due to complex geometry or resonant behavior of radiating elements, a very fine mesh is required. High accuracy analysis is essential and, in this context, full-wave modeling methods play a key role.

A reflectarray can be composed of several thousands of radiating elements, making rigorous analysis of the whole antenna very difficult. Numerical techniques such as the Multilevel Fast Multipole Method permit to treat large structures in terms of wavelength. A quasi-periodic multilayer reflectarray was electromagnetically modeled in [10] but the simulation may suffer from numerical convergence problems for more complex reflectarrays.

Because global simulations require prohibitive CPU time and memory resources, segmented approaches have been implemented. They consist in determining the field radiated by each cell and, in agreement with the superposition principle, the radiation pattern of the global antenna is computed by summing all the unit-cell contributions. The isolated cell approach [11] evaluates the unit-cell radiated field by analyzing the field scattered from the cell without considering the effects of its surrounding elements. The Floquet approach [12] considers that each radiating element is extracted from an infinite periodic array. This method does not take into account accurately the mutual coupling given that it assumes that the individual element is surrounded by identical neighbors. The 'surrounded-element' approach [13] simulates each radiating cell with its actual neighboring cells. The mutual coupling effects are realistically accounted for and better results are reported using this method. The extended local periodicity technique [17] combines the 'surrounded-element' method and the Floquet approach to analyze passive reflectarrays. This technique takes into account the first direct neighbors around the central cell and Floquet boundary conditions are then applied to the resulting sub-array. This means an artificial periodicity is introduced at the sub-array level which can be responsible for inaccuracy in coupling evaluation.

For structures with active loads, the computation time can

Manuscript received December 09, 2011. This work is supported by Thales Systèmes Aéroportés, Elancourt, France.

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be reduced using the compression technique [15]-[16]. For reconfigurable reflectarrays, the Floquet approach can be combined to the compression method [17] to analyze a single unit-cell. The unit-cell, extracted from an infinite array of identical cells, is electromagnetically simulated once and a circuit simulation is carried out to derive the cell response as a function of active loads states. This approach is generally dedicated to the study and optimization of a unit-cell.

In this paper, a new technique combining the 'surrounded-cell' approach and the compression method is presented for the analysis of large and complex reconfigurable reflectarrays.

II. Principle

A. General description

As introduced in [18], each cell in the array is studied one after the other in order to compute the reflectarray radiation pattern. To determine the scattered field of one cell, a sub-array made up of the considered cell and its closest neighbors is considered. The whole sub-array is illuminated by the incident wave and the field radiated by the considered cell is determined. Therefore, the mutual coupling between cells is accounted for in a realistic way. The same electromagnetic simulation is used whatever the studied cell given that the cells are geometrically identical and only the state of the active loads differs from one cell to another. Thanks to the compression approach, the specific state of active elements within the considered cell and its neighbors is taken into account afterwards through circuit simulations. In agreement with the superposition principle, the radiation pattern of the global array is then constructed by summing all the unit-cell contributions.

B. Detailed description for the analysis of one cell

For the sake of simplicity, the considered radiating element includes only one active load, which is a diode. In this case, the control is carried out in a digital manner although the method can be immediately applied to an analog control. For convenience, a sub-array composed of the studied cell and its two closest neighbors is considered (Fig. 1). The mutual coupling from further cells is neglected but the method is naturally expandable to a larger sub-array. A normally incident plane wave illuminates the whole sub-array while the radiation surface surrounds the studied cell. The generalization to multiple incidences and polarizations is straightforward. Using Huygens's principle, the field radiated by the considered cell is calculated by integrating the fields on the radiation surface.

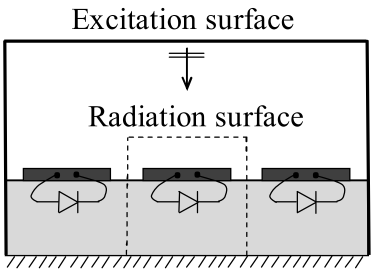

Fig. 1. Structure to analyze.

Step 1. Electromagnetic simulation of the distributed passive part

Diodes are replaced by localized ports and the electromagnetic simulation of the sub-array (Fig. 2) is realized as follows.

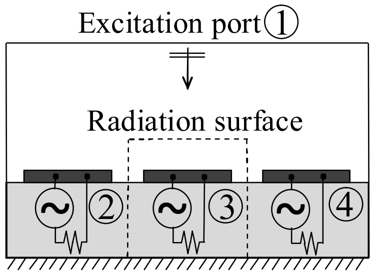

Fig. 2. Electromagnetic simulation of the sub-array.

Each of the localized ports plus the plane wave excitation port is sequentially excited.

Firstly, the plane wave port is excited and the others are terminated with 50-Ohm impedances. An incident wave a_1 is injected and given by

$$a_1 = \sqrt{\left(\left\|\overrightarrow{E_1^{inc}}\right\|^2 S\right)/\eta_0} \tag{1}$$

with:
- S the excitation surface,
- $\overrightarrow{E_1^{inc}}$ the incident E-field on port 1 and,
- η_0 the vacuum impedance.

The normalized far-field $\overrightarrow{\mathcal{E}_1^r}$ radiated from the central cell is recorded, as defined by

$$\overrightarrow{\mathcal{E}_1^r} = \frac{\overrightarrow{E_1^r}}{a_1}. \tag{2}$$

Next, the same procedure is repeated for all the localized ports and $\overrightarrow{\mathcal{E}_{i\ 2\le i\le 4}^r}$ are recorded and obtained as

$$\overrightarrow{\mathcal{E}_{i\ 2\le i\le 4}^r} = \frac{\overrightarrow{E_i^r}}{a_i} \tag{3}$$

where a_i is imposed by the electromagnetic simulator.

At the same time, the reflection and transmission parameters between ports $S_{ij\ (1\le i\le 4, 1\le j\le 4)}$ are determined and gathered in a compression matrix [S]. For the localized ports, the electromagnetic simulator automatically computes the transmission and reflection parameters $S_{ij\ (2\le i\le 4, 2\le j\le 4)}$. For the excitation port, a specific treatment is necessary for the transmission parameters on localized ports. When port 1 is excited, the current and voltage are determined on each localized port and b_i and S_{i1} are deduced as follows

$$b_{i\ (2\le i\le 4)} = \frac{V_i - Z_0 I_i}{2\sqrt{Z_0}} \tag{4}$$

$$S_{i1\ (2\le i\le 4)} = \frac{b_i}{a_1}. \tag{5}$$

Step 2. Compression method

The second step is the compression method. It aims at considering on- and off-state equivalent impedances of diodes. It consists in carrying out the circuit simulation of the loaded sub-array, as described in Fig. 3.

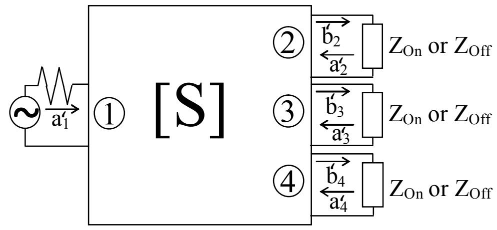

Fig. 3. Circuit simulation of the loaded structure.

A wave a_1' is injected and defined as

$$a_1'=\sqrt{(\left\|\overrightarrow{E_1'}\right\|^2 S)/\eta_0} \tag{6}$$

where $\overrightarrow{E_1'}$ is the desired incident E-field on port 1 of the loaded structure (Fig. 3).

Then, the other coefficients (a_i' and b_i') are computed through a circuit simulation. The expression of $[b']$ is given by

$$[b'] = \left\{ [S]\begin{pmatrix} \Gamma_1 & 0 & 0 & 0 \\ 0 & \Gamma_2 & 0 & 0 \\ 0 & 0 & \Gamma_3 & 0 \\ 0 & 0 & 0 & \Gamma_4 \end{pmatrix} - I_d \right\}^{-1} \left\{ -[S]\begin{pmatrix} a_1' \\ 0 \\ 0 \\ 0 \end{pmatrix} \right\} \tag{7}$$

with $\Gamma_1 = 0$, $\Gamma_{i\geq 2} = \frac{Z_{On/Off}-Z_0}{Z_{On/Off}+Z_0}$, $Z_0 = 50\Omega$, and I_d the identity matrix.

The incident waves $a_{i\geq 2}'$ are directly deduced: $a_i' = \Gamma_i b_i'$.

Step 3. Superposition of the contribution of each port

The radiation pattern of the loaded cell is obtained by summing the contribution of each port.

$$\overrightarrow{E_{cell}^r} = \sum_{k=1}^{4} a_k' \, \overrightarrow{\mathcal{E}_k^r} \tag{8}$$

C. Advantages of the proposed method

The major advantage of the method is that it allows actual mutual coupling effects to be accounted for.

Secondly, this method leads to a drastic reduction of the computational costs compared with global approaches. It requires only one lightweight electromagnetic simulation for the whole antenna.

Moreover, the radiation pattern of any reflectarray configuration of the active elements is determined promptly by circuit simulations.

Furthermore, the proposed method is a flexible technique. It is independent of the number of cells in the array and it is expandable to analyze electrically large reflectarrays.

Four examples are considered to demonstrate the performance and the applicability of the proposed method for solving the electromagnetic problems associated with reconfigurable reflectarrays.

III. Results

A. Presentation

THALES Systèmes Aéroportés has developed a reflectarray design and a detailed description of the cell can be found in [19]. The unit-cell consists of a printed circuit with RF switches inside an opened rectangular metallic cavity (Fig. 4).

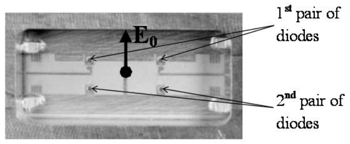

Fig. 4. Reflectarray phase shifting cell.

The digital phase control is provided by two pairs of PIN diodes located on the printed circuit which leads to four possible states as depicted in Table I. The reflectarray operates in the X-band and optimal performance in radiation has been demonstrated in a 25% frequency bandwidth. Diodes have a forward resistance of 2.5 Ohms (Z_{On}) while their reverse blocking capacitance (Z_{Off}) is 50 fF. The reconfigurable reflectarrays studied below are analyzed at 8.7GHz and the size of a unit cell is 0.35λ in the E-Plane and 0.72λ in the H-Plane.

The electromagnetic HFSS® commercial software, which is based on the Finite Element Method, is used and the unit-cell design used for the simulation is represented in Fig. 5. The design does not include biasing lines and, for the validation, an impinging plane wave under normal incidence is assumed.

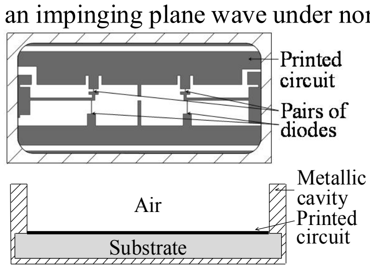

Fig. 5. Unit-cell design for the simulation

A 360° phase range is achieved with about 90° progressive steps between the four states (Table I). The phase values are obtained combining the Floquet approach with the compression method. However, the results are strictly the same than those obtained with the Floquet method. The only difference concerns the computation time which is reduced thanks to the compression method. For the sake of simplicity, the method is just called the Floquet approach.

TABLE I
PHASE VALUES OF THE CELL RESPONSE UNDER NORMAL INCIDENCE AT 8.7GHZ WITH THE FLOQUET APPROACH

State	Phase
On-On	31.0°
Off-Off	-49.0°
On-Off	-123.6°
Off-On	-175.8°

B. Number of cells required in the sub-array

For the considered cell, a preliminary study is done in order to determine the required size of sub-arrays. This size depends of the mutual coupling between cells and does not depend of the total array size. The study consists in comparing the phases obtained by the Floquet approach to those obtained by the proposed method with 3x3, 5x5 and 7x7 uniform sub-arrays.

Given that the Floquet approach analyzes an infinite periodic structure, the phases should be closer as the number of cells in the sub-array increases. Firstly, a 3x3 sub-array with all the cells in “On-On” state is simulated and the radiation surface surrounds the central cell, as depicted in Fig. 6. Then, the phase of the co-polarization component of the electric field, radiated by this cell for θ equals 0°, is determined.

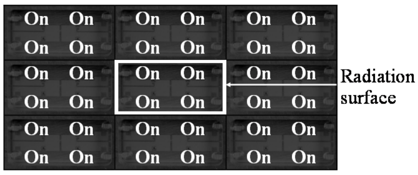

Fig. 6. 3x3 sub-array with all the cells in “On-On” state.

The same procedure is carried out for the three other states and with 5x5 and 7x7 uniform sub-arrays. The results are reported in Table II and they are compared to the phases obtained with the Floquet approach (Table I).

TABLE II
PHASE VALUES OF THE CENTRAL CELL WITH 3X3, 5X5, AND 7X7 SUB-ARRAYS UNDER NORMAL INCIDENCE AT 8.7GHZ

Phase / State	3x3 sub-array	5x5 sub-array	7x7 sub-array
On-On	45.9°	26.6°	33.0°
Off-Off	-45.1°	-48.1°	-51.4
On-Off	-125.3°	-127.1°	-119.7°
Off-On	-183.8°	-179.8°	-171.8

According to the results, a maximum of 15° occurs between the Floquet approach and the proposed method with 3x3 sub-arrays. When 5x5 and 7x7 sub-arrays are considered, the difference between the Floquet approach and the proposed method is approximately 4°. This residual error can be related to the numeric error introduced by the electromagnetic simulation which is more complex when the number of cells increases. As a consequence, 5x5 sub-arrays are sufficient to estimate the mutual coupling effects in reconfigurable reflectarrays of any size composed by this type of cells.

C. Validation of the method with a 10x10 reflectarray

A small-sized array of 10x10 cells is studied so that it can be simulated entirely with HFSS for validation. This simulation of the global antenna is the reference simulation and allows to compare results from different approaches.

The array is illuminated by a normal-incident plane wave and the aim is to steer the direction of the main beam in the (φ_{max} = 45°; θ_{max} = 10°) direction. To do so, the state of all diodes is determined according to the relevant phase law using Floquet phase values (Table I) and the configuration of the diodes is depicted in Fig. 7.

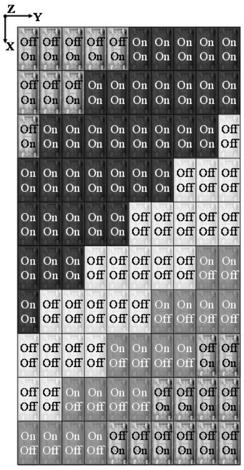

Fig. 7. 10x10 array with a main beam in the (φ_{max} = 45°; θ_{max} = 10°) direction

The reconfigurable reflectarray is simulated with three different approaches:

- The global simulation of the reflectarray replacing the diodes with their equivalent impedances (reference),
- The Floquet approach,
- The proposed approach with 5x5 sub-arrays.

The radiation patterns obtained with the three approaches are reported in Fig. 8.

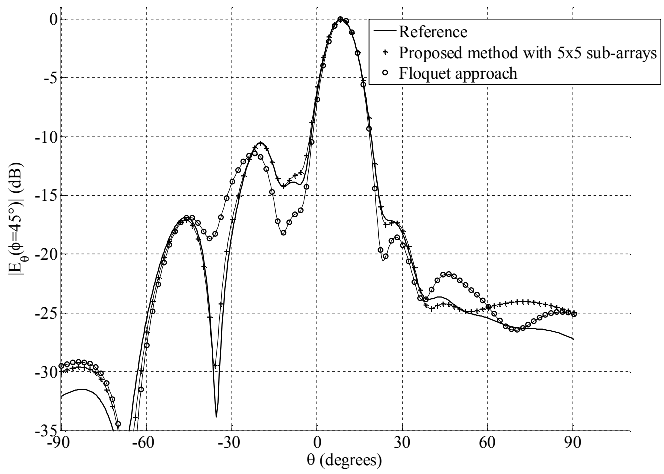

Fig. 8. Comparison of the proposed method with 5x5 sub-arrays and the Floquet approach for a 10x10 reflectarray.

First of all, the results achieved with the proposed method are in good agreement with those obtained with the reference simulation. Secondly, the proposed method gives better results than the Floquet approach. However, in this case, the Floquet approach is acceptable given that few diode states discontinuities exist on the reflectarray.

In order to provide a more quantitative assessment, the statistical results set out in Table III compare the two different approaches to the reference simulation. The PL_{error} parameter estimates the field amplitude difference between the studied approach and the reference in the main lobe direction. This error is 0.09dB for Floquet and 0.07dB for the proposed method. The MAE parameter, which stands for ‘Mean Absolute Error’, is the average of the absolute differences between the method and the reference for θ over the interval [-

90, 90] degrees. The MAE is equal to 0.91dB with the proposed technique using 5x5 sub-arrays and 1.93dB with the Floquet method.

TABLE III
STATISTICAL RESULTS

	Floquet	Proposed method with 5x5 sub-arrays
PL_{error} (dB)	0.09	0.07
MAE(dB)	1.93	0.91

Besides, all the computations are carried out on an Intel® Xeon® E5506 2.13GHz Quad Core with 48 GB RAM. The simulation of the global antenna requires 587 minutes for each reflectarray configuration of the diodes. In comparison, the electromagnetic simulation of the 5x5 sub-array requires 201 minutes and the circuit simulation performed to consider the state of active elements requires only 55 seconds. In this example, one specific configuration is studied but the method can easily analyze any configuration. In conclusion, the proposed method using 5x5 sub-arrays has been validated on a simple case and has proved to be accurate.

D. Analysis of a 10x10 reflectarray

A second example of a small-sized array of 10x10 cells is studied. This example is not a practical one but the purpose is to show that the proposed method is more robust than the Floquet approach.

The array is illuminated by a normal-incident plane wave and the aim is to steer the direction of the main beam in the (φ_{max} = 45°; θ_{max} = 30°) direction. The configuration of the diodes in the array is represented in Fig. 9.

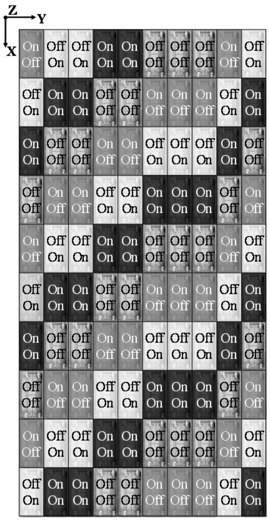

Fig. 9. 10x10 array with a main beam in the (φ_{max} = 45°; θ_{max} = 30°) direction

As in section *B*, the reconfigurable reflectarray is simulated with three different approaches and the radiation patterns are reported in Fig. 10.

A difference of approximately 2.5dB exists for the first quantification lobe between the reference and the Floquet approach. There is a noticeable difference of 9.7dB for the second quantification lobe between the reference and the Floquet approach while the proposed method is in good agreement with the reference. The Floquet approach is not accurate since strong variations of cell states are encountered on the reflectarray. The infinite array assumption is not acceptable in this case.

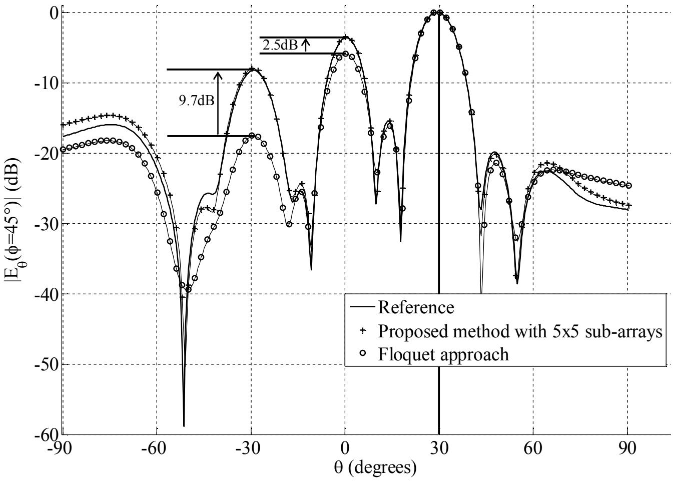

Fig. 10. Analysis of a 10x10 reflectarray with the proposed method with 5x5 sub-arrays, the Floquet approach and the global simulation.

As depicted in Table IV, the PL_{error} is 0.36dB for Floquet and 0.21dB for the proposed method. With the proposed technique using 5x5 sub-arrays, the MAE is equal to 0.86dB which is less than the 2.89dB obtained with the Floquet method. For the two parameters, the proposed method with 5x5 sub-arrays is more accurate than the Floquet approach.

TABLE IV
STATISTICAL RESULTS

	Floquet	Proposed method with 5x5 sub-arrays
PL_{error} (dB)	0.36	0.21
MAE(dB)	2.89	0.86

E. Analysis of a uniform 50x50 reflectarray

A more complex case has been chosen to show the capability of the technique for analyzing larger reflectarrays without a considerable increase in the processing time.

The considered reflectarray is now composed of 50x50 cells and is illuminated by a normal-incident plane wave. All the diodes within the array are in the same state and thus the infinite array environment assumption is justified. Then, the Floquet approach is expected to be accurate.

The analysis of the global antenna using a standard rigorous method, like the FEM (Finite Element Method), is impossible. Fig. 11 shows the far-field patterns obtained using the proposed method and the Floquet approach. The agreement between the two approaches confirms the effectiveness of the proposed method on larger reflectarray.

Moreover, to analyze the 50x50 reflectarray, the proposed method with 5x5 sub-arrays requires, as before, 201 minutes for the electromagnetic simulation. The only difference concerns the post-processing which requires 18 minutes instead of 55 seconds for the 10x10 reflectarray.

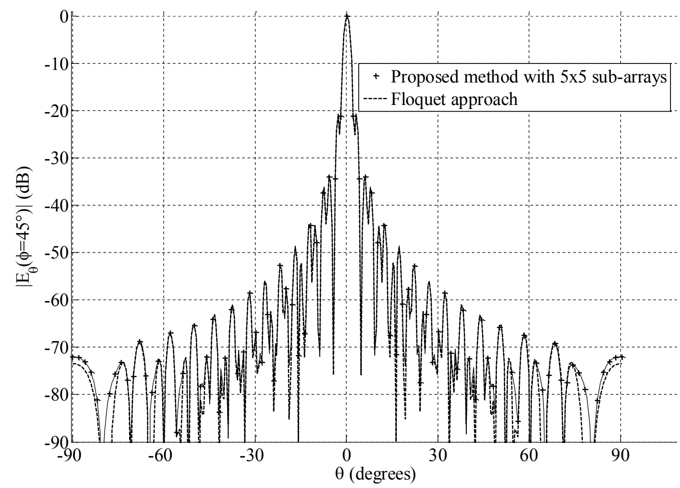

Fig. 11. Simulation of a uniform 50x50 reflectarray using the proposed method with 5x5 sub-arrays and the Floquet approach.

F. Analysis of a 50x50 reflectarray

As for the first example, the states of diodes are now chosen to steer the beam in the (φ_{max} = 45°; θ_{max} = 10°) direction and the array is illuminated by a normal-incident plane wave.

The radiation patterns are reported in Fig. 12. A difference of 1.6dB and 3.5dB exists for the first quantification lobes between the proposed method and the Floquet approach. Contrary to the precedent 50x50 array example, this array is not uniform and the Floquet approach does not take into account accurately the mutual coupling. As a consequence, the Floquet approach can't be accurate and the proposed method gives better results.

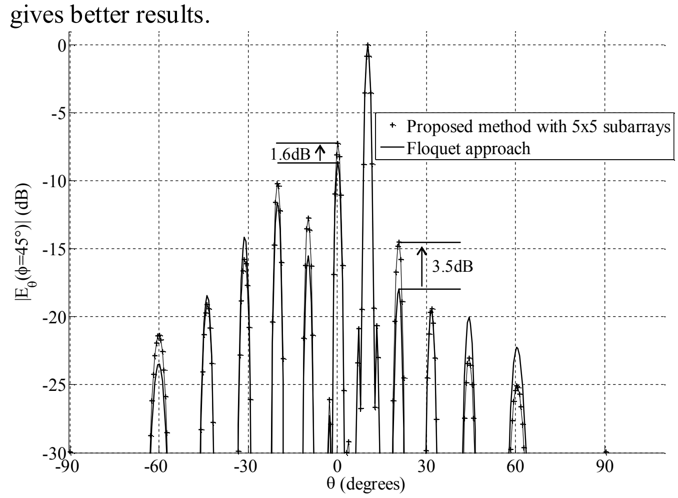

Fig. 12. Simulation of a 50x50 reflectarray using the proposed method with 5x5 sub-arrays and the Floquet approach.

IV. CONCLUSION

A fast technique to simulate reconfigurable reflectarrays with mutual coupling consideration has been described and validated. It was shown that the proposed technique is more accurate than the Floquet approach. The efficiency and strength of the proposed method has been proved for the analysis of two 10x10 and two 50x50 reconfigurable reflectarrays. Furthermore, this method is well-adapted for any kind of reconfigurable reflectarray no matter what the configuration of the active elements is and how large the array is.

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